

Propulsion/ACEE

Ten billion gallons of aviation fuel are burned each year by the commercial airlines in the United States. Improving the energy efficiency of contemporary and future jet engines by only five percent would result in saving five hundred million gallons of fuel each year.

The simple facts of these huge numbers are the underlying premise of the propulsion studies in the Aircraft Energy Efficiency (ACEE) program managed by the National Aeronautics and Space Administration.

The basic goal of the ACEE program is to learn how to use fuel energy more efficiently for propulsion. That, in turn, will reduce the factor of energy costs in air transport operations, military flight operations, and in

the broad and rapidly growing field of general aviation.

ACEE is a ten-year planned program that was first developed as a response to a request from the United States Senate Committee on Aeronautical and Space Sciences. It looks simultaneously at both near- and far-term problems. It attempts to develop expedient solutions that can be applied to contemporary transport aircraft, to their derivatives expected in a few years, and to wholly new classes of transports designed specifically to be fuel-efficient.

The workload of the ACEE program is divided among several NASA research centers. NASA's Langley Research Center, Hampton, Virginia, is responsible for tech-

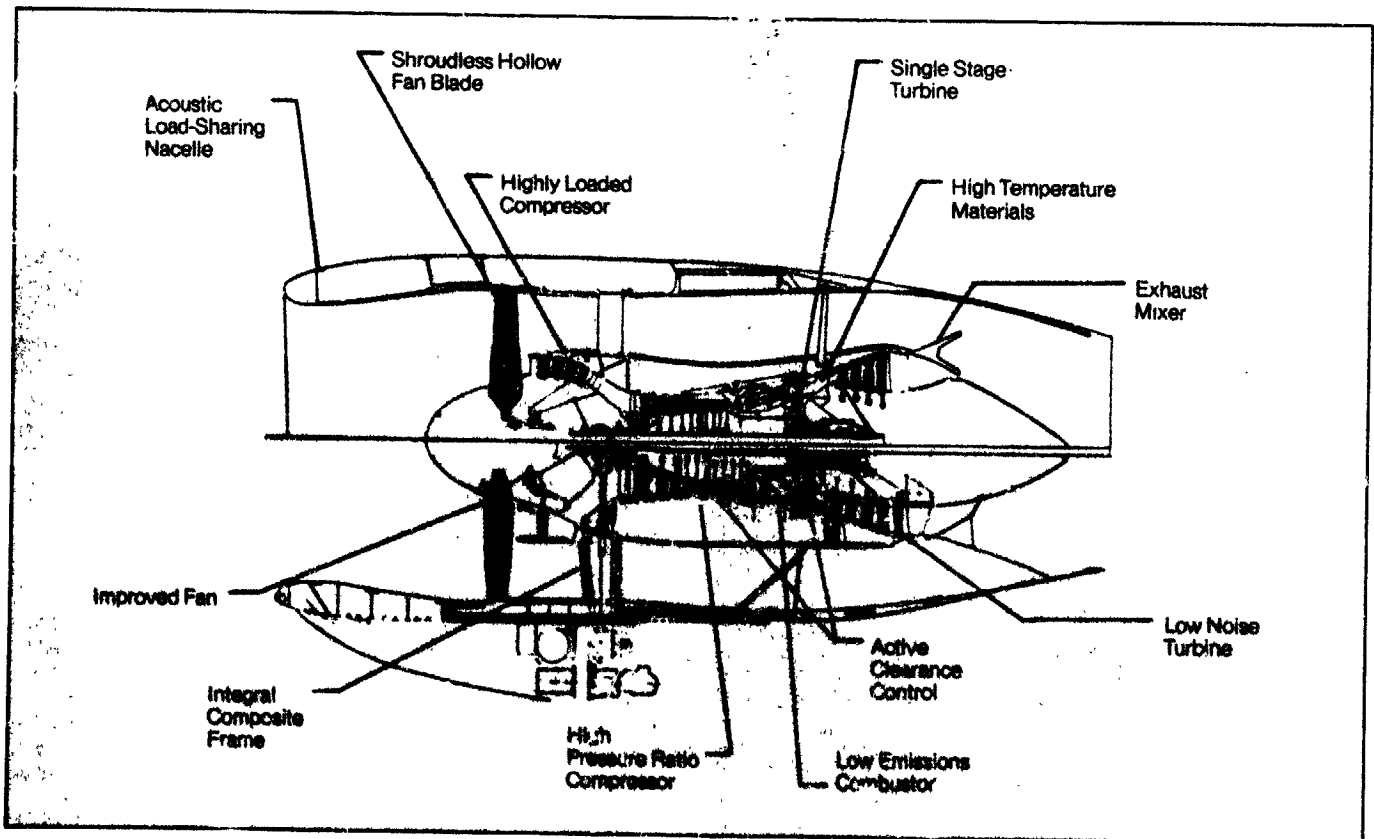


Figure 1: Part of the NASA Energy-Efficient Engine program consisted of identifying those components of contemporary powerplants that were candidates for further improvement, based on current and projected states of the art. Here a number of them have been indicated on a single cross-section of a typical turbofan engine. Some are aerodynamic, such as a high-pressure-ratio compressor, or an improved fan. Others are structural, such as the high temperature materials suggested for the turbine section. The point is to show that each of these improvements, while of itself producing only a small percentage gain in performance, combines in a synergistic way to drive a major improvement of the complete engine.

nology studies in aerodynamics, and in materials and structures. The wind-tunnel testing is shared by Langley and the Ames Research Center, Moffet Field, California. Flight experiments are conducted by the Dryden Flight Research Center, Edwards, California. Propulsion research—the subject of this publication—is done by the scientists and engineers at the Lewis Research Center, Cleveland, Ohio.

NASA is joined by other organizations in this work. The airlines, the ultimate users of the technology, have furnished valuable input with contracted studies of their real-world operations as applied to the concepts of energy-efficient aircraft. Airframe and engine manufacturers, possessing their own research facilities as well as full-scale engines and aircraft to test, also are a part of the ACEE team.

Overall, the broad purpose of the program is to provide an inventory of technology that can be used by the major manufacturers of transport aircraft and engines in the United States. It will help them develop near-term derivative airliners that extend their current product lines, to develop families of new designs for the near term, and perhaps to develop radically different aircraft for the far term.

It's important to note that NASA had been studying the problems of energy-efficient aircraft some years before the fuel crisis focussed such critical attention on them. NASA's Advanced Transport Technology program, begun in the early 1970s, had as one goal the determination of the effect of a number of different new technologies on fuel consumption. Many of the same technologies under study then—such as quiet propul-

sion systems—became foundation stones of the current ACEE program.

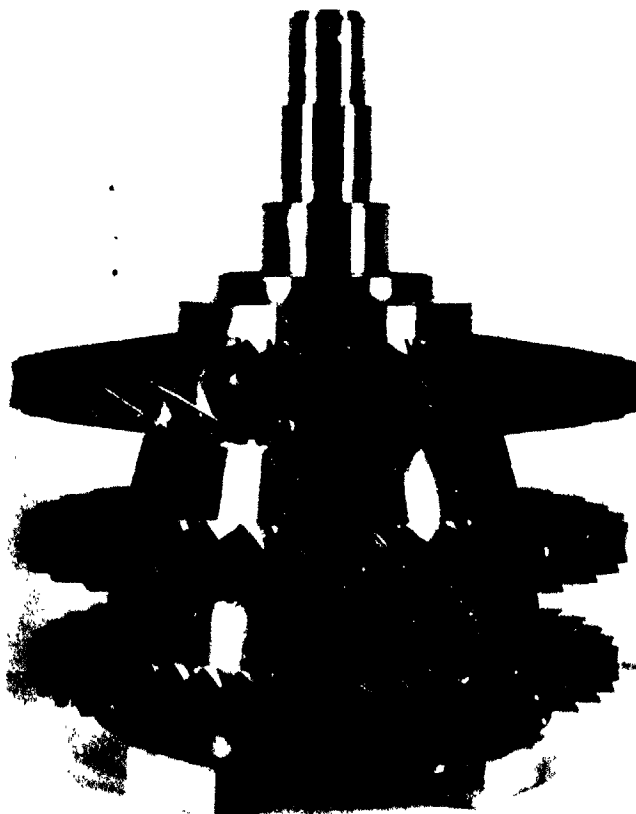
Three of its six components relate to propulsion: Engine Component Improvement (ECI); Energy Efficient Engine (EEE); and Advanced Turboprops (ATP).

Engine Component Improvement

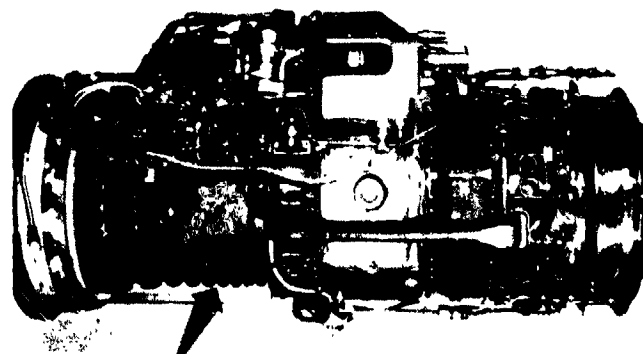
Four commercial jet engine models power almost all of the U.S. jet transports and burn almost all of that ten billion gallons of fuel per year. One of those engines is at the end of its production road; no future aircraft designs are being planned around it. But the other three are still in active development and use, and give every indication of being on the air transport scene for at least another decade or so. By concentrating on component improvements for those three, NASA hopes to show the way to major fuel savings in the decade of the 1980s.

Now, new components designed with the aid of the technology developed in the ECI program are being introduced in production. For the future, a better understanding of design technology could produce engines that will have a minimum of performance fall-off with time, currently the enemy of jet engine thrust and fuel consumption.

Part of the ECI program is a continuing careful study of engine diagnostics. As an engine runs in everyday use, it is subjected to wear and to small damages. Sand, dust or tiny stones cause nicks in the fan blades. The tips of the compressor blades wear down. The combustors, operating with a high-efficiency fire inside their



Low Aspect Ratio Compressor



Conventional Compressor

Figure 2: The advantage of advanced compressor design technology is that it enables the engine to do more work with less fuel. Here a three-stage compressor of advanced design is shown to compare its layout to that of a conventional compressor of six stages. Advantages of the advanced design compressor stem from its improved blade design, which is aerodynamically more efficient. It therefore produces its desired compression ratio with fewer blades, which in turn means a lighter and less expensive item to produce. This design showed a further advantage. The ability to retain its performance nearer the design peak even after successive service and overhauls.



Figure 3: Wind-tunnel tests of advanced turboprop designs, like this eight-bladed unit shown in one of the facilities at the Lewis Research Center, are used to explore the performance characteristics of these unusual concepts. They also help to define propeller noise levels, a major consideration not only for "good neighbor" reasons, but also because high-intensity noise can damage adjacent structure on an aircraft. These tests also assist in developing analytical techniques for predicting the acoustic performance of such propellers.

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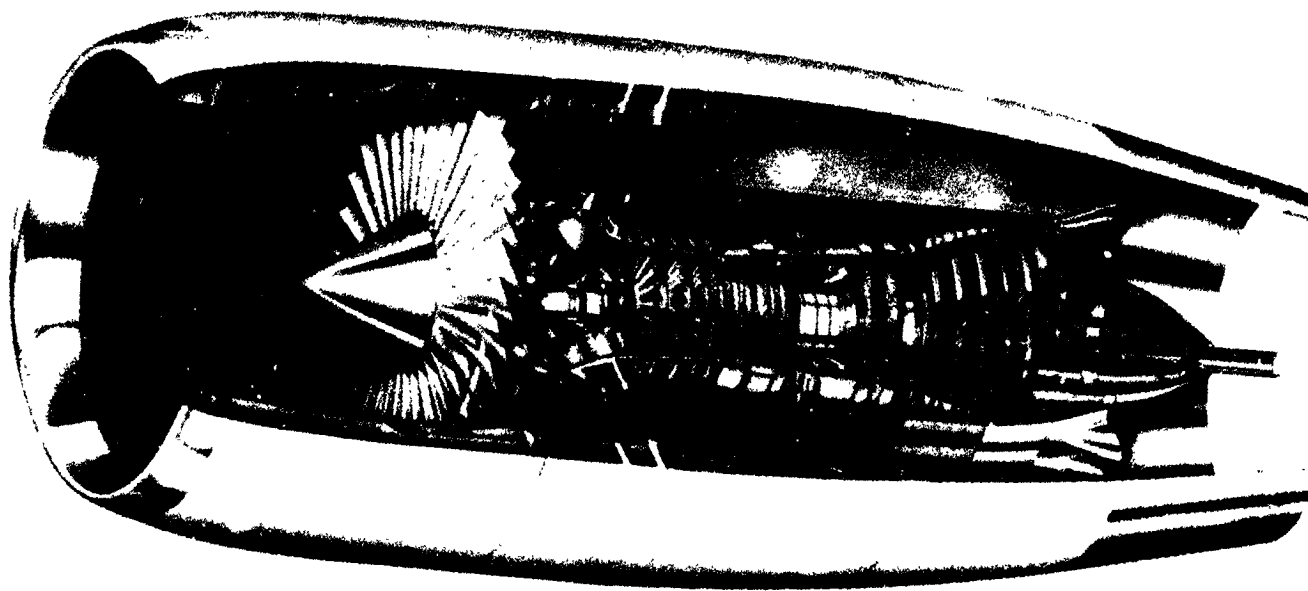


Figure 4: NASA contracted for studies of advanced high-bypass-ratio engines to define a completed unit around which a component development program could be organized. Both General Electric Co. and Pratt & Whitney Aircraft developed their individual concepts to the level of "paper" engines, similar in general layout but differing in detail. This cutaway drawing shows the concept developed by General Electric.

thin shells, warp under the heat. Seals that keep hot gases contained and directed develop leaks. The turbine blades, whirling at high speed in the blast-furnace discharge of the combustors, erode under the high-temperature, high-speed gas flow.

The result is that engine thrust decreases with each hour of passing time; the fuel consumption increases during the same running hour. Overhauls of the engine restore only a part of the lost performance; the engine re-enters service with a lower thrust and a higher fuel consumption than it had when new. Each time the cycle repeats, the engine gets a little worse in performance. The goal of the diagnostics program, being conducted by NASA with assistance from the engine manufacturers and the airlines, is to reduce that deterioration by several percentage points.

Ground tests and in-flight monitoring of both new and used engines are being analyzed carefully to determine just what are the causes of the performance deterioration. Once those factors are uncovered, then design information can be derived which will improve both existing and new engines by making them less subject to performance degradation.

Specifically, two turbfans with high bypass ratios have been singled out for detailed diagnostic studies. The initial performance deterioration trends were determined from historical analysis of ground flight tests, as well as from a knowledge of what parts had to be

replaced during the life cycles of the engines. Operational engines also were analyzed to obtain current data from powerplants that had been ground-and flight-tested, torn-down and inspected. That analysis was used to identify and to quantify the causes of performance fall-off.

The results indicate that it is engine cycling — the start-up, running, and shut-down — and not only operating time, that is the major factor in performance reduction. Most of the loss comes from high-pressure compressor and turbine; about two-thirds of the deterioration is caused by those two, with the compressor becoming increasingly responsible as the number of flight cycles increases.

The fastest rate of deterioration occurs during the early cycles; that is because the seals wear and the clearances around them increase. Within the first few hundred hours of running time, fuel consumption increases about one percent. By 5,000 hours of running time, not much more than 16 months service life in a typical airline operation, the fuel burning rate is up about three percent.

If the engine is overhauled and repaired at that point, it will gain back about one percent of the specific fuel consumption, but the engine will still be two percent worse than when it came from the factory.

Information from the engine diagnostics program also has demonstrated that costly unscheduled engine removals can be reduced by as much as 50 percent.

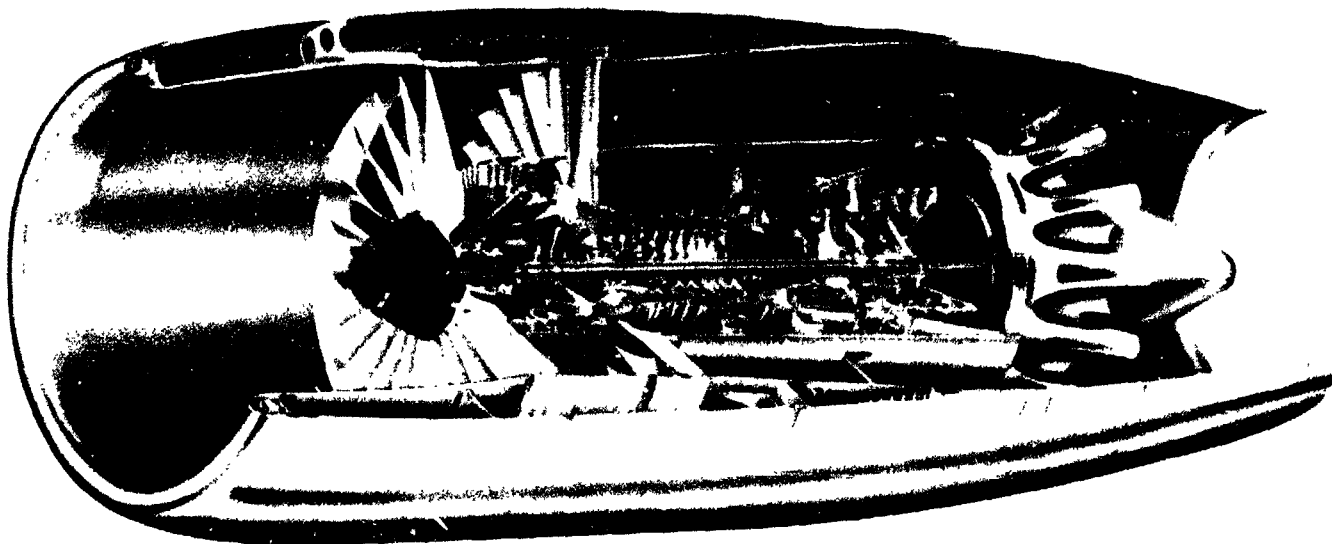


Figure 5: For their designs of Energy-Efficient Engines (EEE) as part of NASA's ACEE program, both contractors designed complete paper engines incorporating the latest technologies. Both suggested a major increase in the bypass ratio, to levels between 6.5 and 7.0. Both suggested that overall pressure ratios be higher. And both went for increased turbine operating temperatures, near the limits available with current technology. This cutaway shows the engine designed by Pratt & Whitney Aircraft for the EEE portion of the ACEE program.

Concepts from Industry

When the performance improvement phase of the ECI program began, the two manufacturers of jet transport engines were asked to submit lists of candidate concepts for component modification. General Electric submitted 60, and Pratt & Whitney suggested a list of 70.

They were evaluated by a team that included representatives from the engine companies, as well as from airframe and airline companies and NASA. Initial screening reduced the list to 16 items that were considered of overriding importance and potentially significant for further development.

They were in five general areas: Component aerodynamics; seals in the airflow path, control of blade tip clearances; materials and coatings for the turbines; and the aerodynamics of the exhaust nozzle and the nacelle.

A jet engine behaves somewhat like a pump, it takes in air at the front and pumps it out the back, moving it faster through the exhaust than through the inlet. The extra energy comes, of course, from burning fuel in the air. A pump that leaks is, obviously, inefficient; a jet engine that leaks its high-pressure heated air also is inefficient. The task of the designers of improved components includes stopping a lot of leaks.

They exist in seals that are intended to keep hot high-pressure gases from finding their way out of the

main flow path and into the engine housing. They exist between the tips of the rotating fan, compressor and turbine blades, allowing air to leak past without being properly handled by the rotating part.

Consequently, both seals and tip clearances receive major attention in the ECI program, for each of the engines under study.

Improved aerodynamic design of compressor and turbine blades can increase engine efficiency. By using new materials or ceramic coatings, erosion and corrosion of the blades can be reduced. A better cooling system for the turbine, and coated blades, can reduce the amount of air needed to cool the hot section and further improve efficiency.

The planned evolution of this program, which started with the screening process, has led to a series of tests made in appropriate model form in component rig research. Following the completion of that phase of the ECI work, many of the major improvements will be built and tested, full-scale, on an instrumented engine running in a test bay.

The ECI program had produced major successes by early 1980. Seven of the concepts had completed development, and four of them were in production in response to airline orders. Some of the concepts will be applied to engines sold to power the new Boeing 767 and the McDonnell Douglas DC-9 Series 80 aircraft. The total estimated fuel savings to be realized by the ECI program is \$9 billion during the next 25 years.

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Figure 6: Electronic beam welding was used to fasten the halves of the split front vane casing for the high-pressure compressor of Pratt & Whitney's proposed Energy-Efficient Engine



Figure 7: The separated components of the high-pressure compressor casing of the Pratt & Whitney Energy-Efficient Engine design are shown here before electron-beam welding

As in so many NASA programs, the goal of the Energy Efficient Engine (EEE) program is to provide a technology base, first by proving a concept and then by testing and evaluating it under controlled conditions

The concept is an engine with higher thermodynamic and propulsive efficiencies, which is environmentally acceptable, and which has a 12 percent reduction in specific fuel consumption, a five percent reduction in direct operating costs, and a 50 percent improvement in performance retention. These improvements, of course, are compared to baseline data on contemporary high bypass ratio turbofan engines.

A turbofan engine uses an extra set of rotating blades, placed out ahead of the working core of the engine like a small propeller. The fan—that extra set of blades—is driven directly by power from the turbine. The fan propels a stream of air that goes through the core and around the outside of the engine, bypassing the core. The bypass ratio is the ratio of the amount of that bypass air to the amount that goes through the core. When that ratio is around four or five, the engine is called a high bypass ratio engine.

They are basically very efficient engines, compared to the first and second generation of jet and fan engines that were developed in the 1950s and 1960s. They power the new generation of wide-bodied jet transports and they have a potential for further development.

NASA contracted with General Electric and Pratt & Whitney to define an advanced high bypass ratio (HBR) engine around which the NASA component development program could be planned. Both companies developed their own concepts, similar in general but different in some important details. Both suggested a major jump in bypass ratios, to levels between 6.5 and 7.0. Both suggested higher overall pressure ratios. Both suggested turbine operating temperatures at the upper limit of today's top operating range.

The two contractors selected the optimum size, thrust level, the operating thermodynamic cycle, and the basic geometry of the engines. Then, given these two different engine concepts, NASA planned the component development work.

It was clear that contemporary technology was ruled out from the start, it is not capable of producing the improvements needed to make these new concepts a reality. Consequently, completely new components were required from front to rear of the engine: Fan, compressor, combustor, high-pressure turbine, low-pressure turbine, and mixer. Each of these, plus the nacelle suggested as the optimum way to house the engine, became subjects of the EEE investigations.

The timetable calls for component testing to be completed during the early 1980s. Before then, some of the results will be fed into the design of a core engine, combining the compressor, combustor, and high-pressure turbine. That core could undergo testing sometime during the early 1980s, and be ready to provide the technology base any time after that.

The approach is the standard building-block technique used by engine manufacturers in their development of military and commercial powerplants. They typically start with a single new component, and refine it, and

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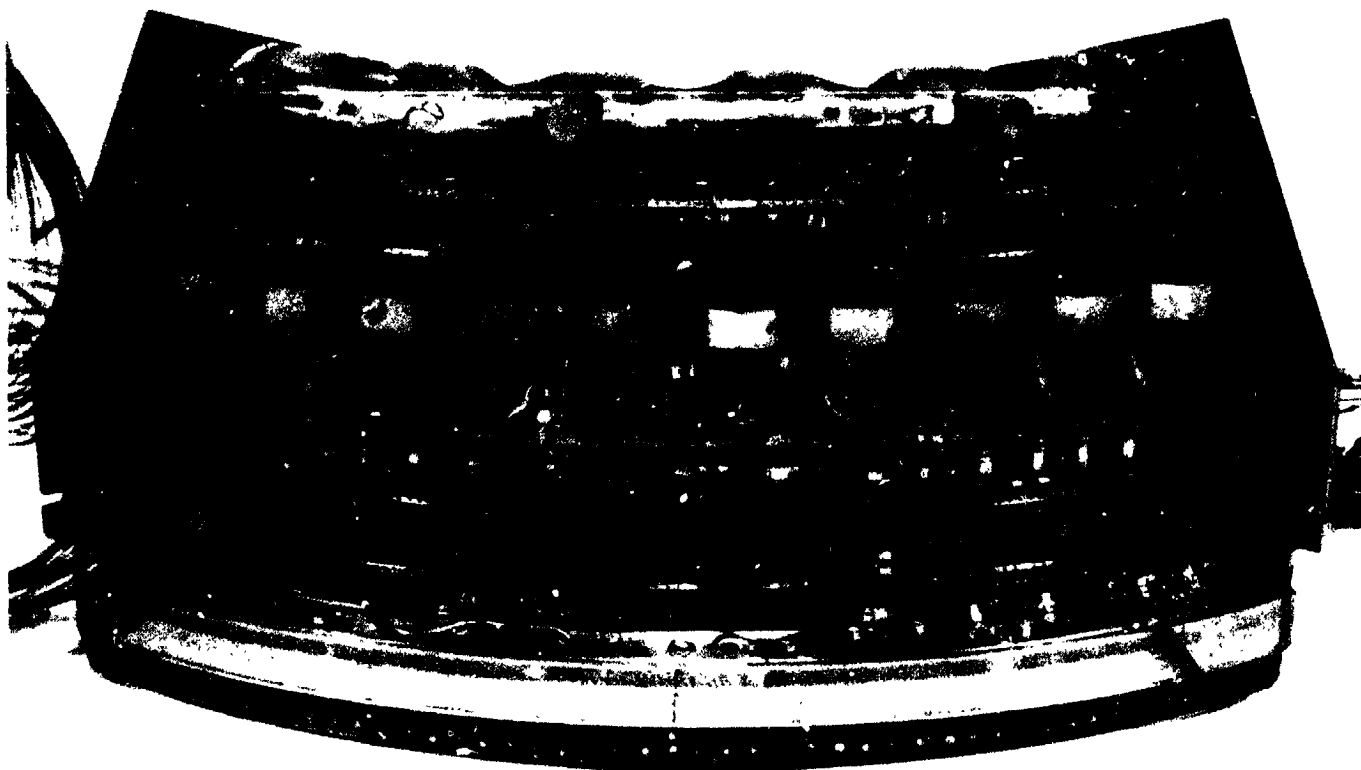


Figure 8: This test rig, a sector of the proposed combustor of P&W's EEE design, shows the carburetor tubes used as main zone fuel injectors

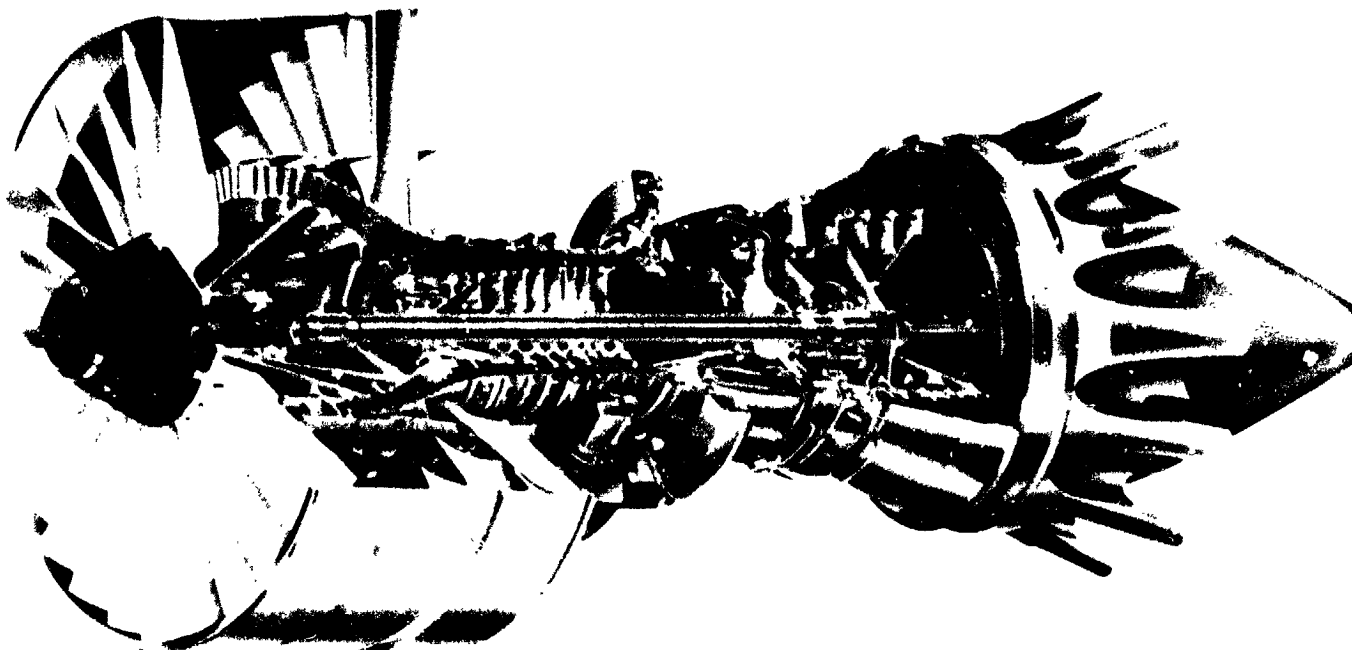


Figure 9: For their designs of Energy-Efficient Engines (EEE) as part of NASA's ACEE program, both contractors planned complete 'paper' engines incorporating the latest technologies. Both proposed a major increase in the bypass ratio, to levels between 6.5 and 7.0. Both suggested that overall pressure ratios be higher than contemporary values. And both designed for increase turbine operating temperatures, near the limits available with current technology. This cutaway shows the engine designed by Pratt & Whitney Aircraft for the EEE portion of the ACEE program.

then use it as the basis for design of a new or improved engine. Later, another component might follow the same road before being incorporated in a new production engine.

Once the core has been built and tested in full-scale, it will be augmented by the addition of the fan, the low-pressure turbine section, and the exhaust nozzle, to complete the engine.

Much of the technology incorporated in the energy-efficient engine designs is directly related to results from other NASA-supported activities. One typical example is the high-pressure compressor design, which evolved from the high-performance, high-speed unit defined during earlier advanced compressor design studies. It is a compressor that uses only ten stages of blades with a stubbier shape than usual. These low-aspect-ratio blades improve the compressor's work per stage, aerodynamic performance, and resistance to foreign object damage and erosion. As a bonus to reduce manufacturing and overhaul costs, the compressor has as many as 40 percent fewer parts than the equivalent conventional compressor that it replaced.

The new design showed efficiencies of better than 90 percent per stage, which is higher than current engines achieve. Further, it maintained that level of performance for a longer time, thus reducing the amount of engine performance degradation with time and operating cycles.

In addition to the advanced compressor design, work has been done on an advanced fan design, with lighter and stronger blades than those of current engines. They will improve the overall aerodynamic performance of the fan, and will reduce fan weight because they will not require blade vibration dampers.

An added component will mix the cooler bypass air with the hot core flow to increase engine propulsive efficiency and reduce noise. The mixer may be like the "daisy" type tested at the Lewis Research Center.

Before the ACEE program began, NASA had done much work on combustor design, seeking to reduce the level of emissions in order to meet the requirements of the U.S. Environmental Protection Agency. The work was done under the Experimental Clean Combustor program, and is applicable to the advanced engine design.

By late 1979, all the experimental test hardware had been taken through the preliminary design stage, and some of the small-scale experiments on pieces of components had begun. Some full-scale component evaluations had started in 1980, and the plans called for reaching the goal of a core demonstration in 1983.

Advanced Turboprops

It may seem like a retrograde step to be considering propeller-driven aircraft this late in the century, with more than two decades of commercial jet transport service behind us. But there are very good reasons to do so, and they have to do with fuel economy.

It is simply more efficient to move an airplane through the air with a propeller than it is to thrust it along by turbofan engine. It is much more efficient than to move



Figure 10: This detail of the P&W EEE combustor rig before assembly shows the main zone and pilot zone fuel injectors

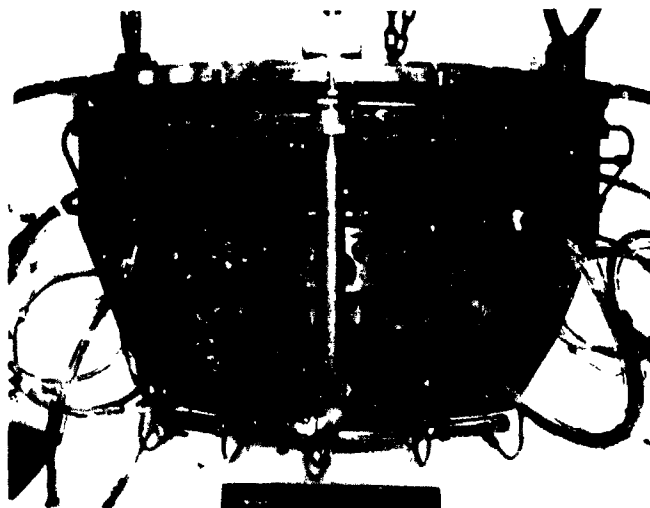


Figure 11: The complete combustor sector rig for the P&W Energy-Efficient Engine is shown here assembled and ready for installation on the test stand

it with a straight jet engine. There are those proponents of propellers who will say that the reason for the relative efficiency of the turbofan engine is really because it is basically a turboprop engine with a shrouded, small-diameter high-speed propeller.

The arguments in the past have centered on speed as the reason for replacing the propeller with a jet propulsion system. Propeller efficiency is higher, but it peaks at a speed lower than the speeds at which jet or turbofan engines peak. The increased efficiency of the pro-

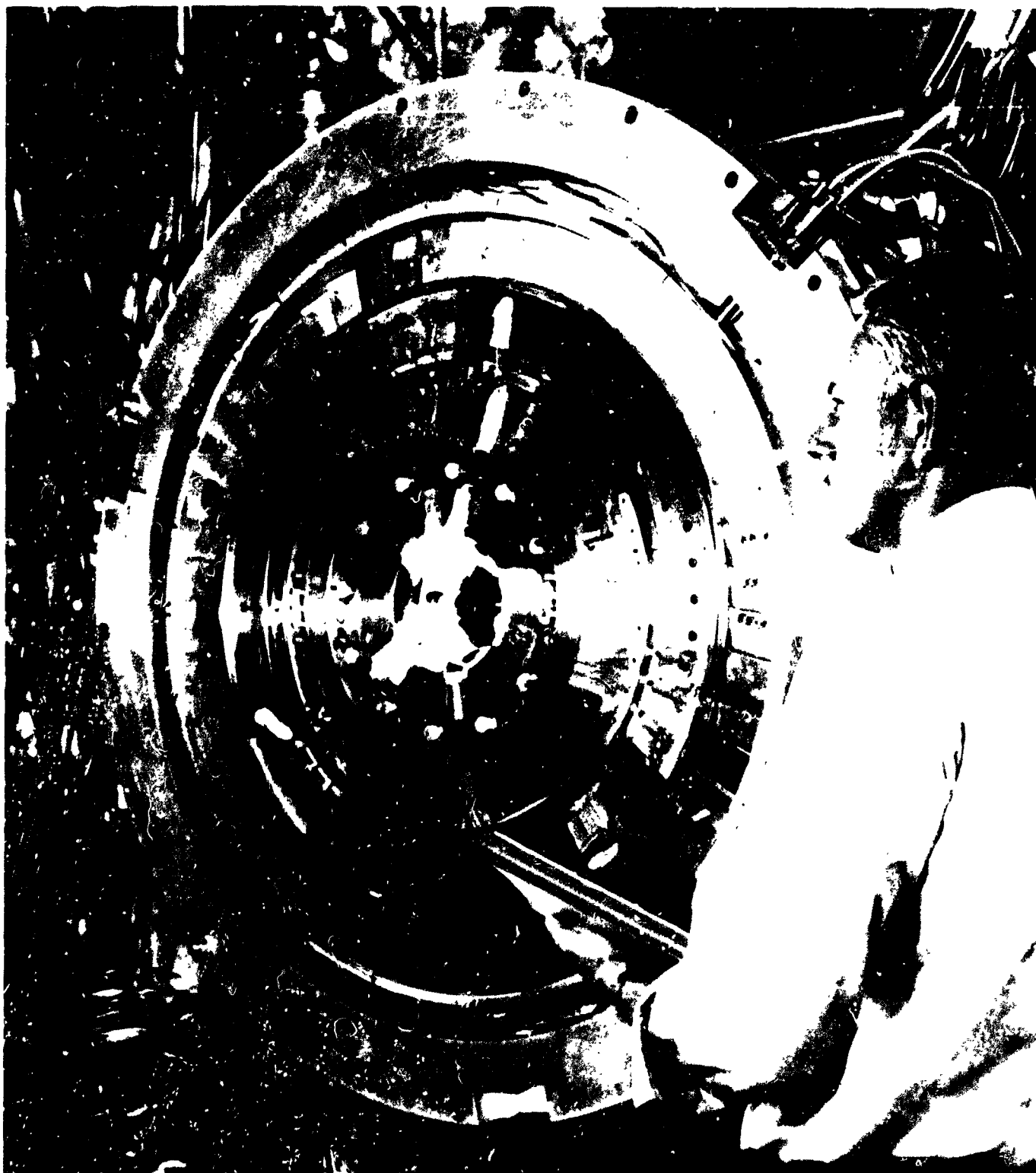


Figure 12. The turbine design for P&W's Energy-Efficient Engine was tested in a single-stage form. Results showed the uncooled aerodynamic efficiency of the high-pressure turbine to be 91.1 percent.

propeller can be translated into fuel savings.

An advanced turboprop propulsion system—an advanced propeller driven by a modern gas turbine through gearing—offers the possibility of saving as much as 20 percent of the fuel burned under equivalent

conditions by an advanced technology turbofan engine.

NASA's advanced turboprop program follows a three-stage schedule. The first is a technology program that will develop a data base, using small-scale propeller models to establish the proof of concept. The second

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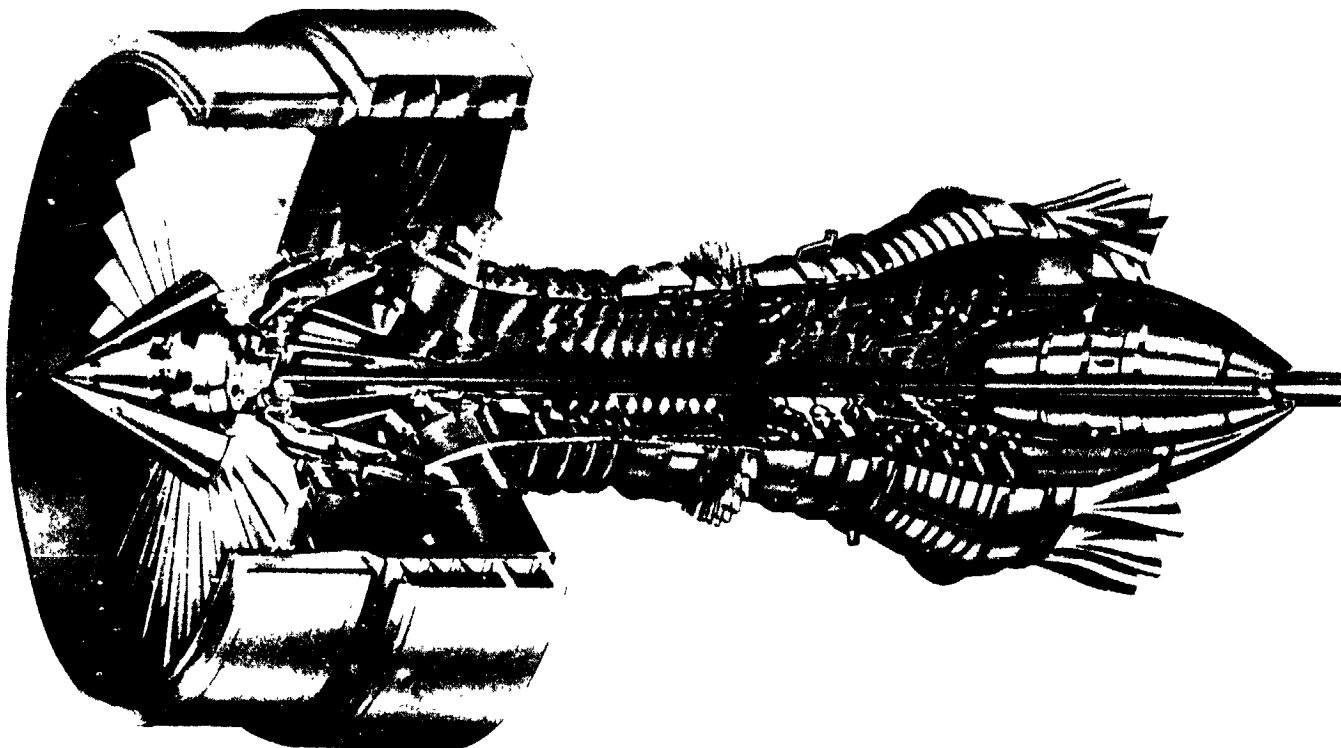


Figure 13: NASA contracted for studies of advanced high-bypass-ratio turbofan engines to define a completed unit around which a component development program could be organized. Both General Electric Co. and Pratt & Whitney Aircraft Group developed individual concepts to the level of "paper" engines, similar in general layout but differing in detail. This cutaway drawing shows the integrated core low spool configuration developed by General Electric.

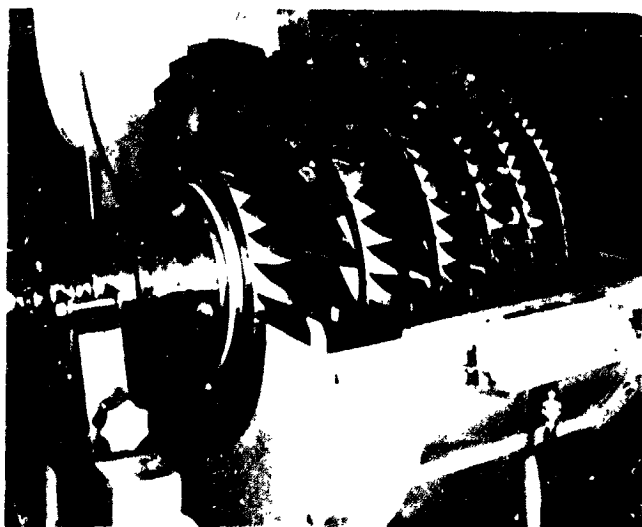


Figure 14: The forward rotor assembly of the high-pressure compressor in GE's Energy-Efficient Engine is shown here in a dynamic balancing machine.

phase deals with the validation of the structural dynamics of large-scale advanced propellers. The third phase plans for the construction of a full-scale experimental propeller and its flight testing on an existing turboshaft engine.

It would be most helpful if such an advanced design would show no speed penalty in comparison to flight

powered by pure jet propulsion. As it now appears, there will be little, if any, such penalty. NASA has demonstrated, in model form, high propulsive efficiencies under conditions that correspond to the cruise speeds and altitudes of today's jet transports.

Note, though, that the modern concept of a proper turboprop engine does not drive a conventional propeller. The new propellers are multi-bladed; the blades are shaped like scimitars, with thin airfoil sections and sweptback tips. The odd-appearing design is necessary to develop the efficiency, power loading, and noise levels necessary to match jet aircraft performance.

Propeller efficiencies on the order of 80 percent are demanded by the high-speed cruise conditions that are foreseen for the advanced turboprop engine. These values are within reach. Hamilton Standard conducted some tests under contract to NASA, using an eight-bladed propeller with the scimitar blades. The prop was run at a simulated flight speed of Mach 0.8, and an altitude of 35,000 feet. It developed an efficiency of just over 78 percent, within two percent of the program goal.

But regardless of efficiency, the advanced turboprop engine will not be accepted unless its noise can be reduced over that of the earlier generation. A major portion of the NASA studies on the ATP is concerned with the measurement and analysis of propeller acoustic properties, and of ways to reduce propeller-generated noise.

NASA has a long history in acoustic studies, and is in a strong position to improve the advanced turboprop

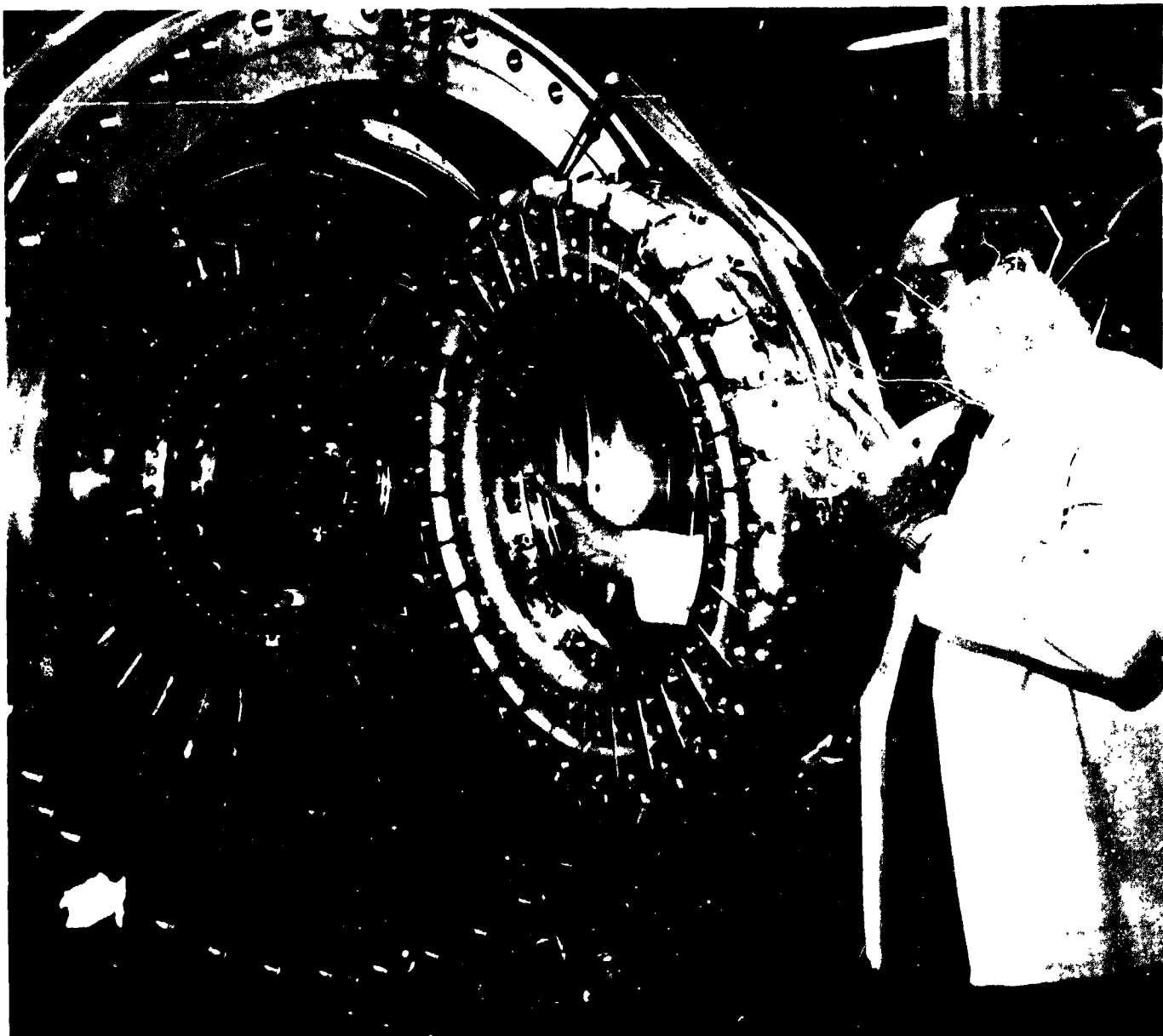


Figure 15: The annular combustor, suspended from a sling as it is being installed in the component test rig, indicates the compact size of the unit, part of the Energy-Efficient Engine designed by General Electric under NASA contract

in that regard. Then, having reduced propeller-generated noise to an acceptable level, NASA can study methods to improve cabin soundproofing, to make the internal perceived sound levels lower. Innovative structural design, and lightweight acoustic insulation are two approaches being evaluated by NASA.

Propeller noise also will be evaluated in model tests, using a scaled-down propeller mounted on a pylon above the fuselage of NASA's Lockheed JetStar light transport. These tests will study the problem in free air, under conditions approaching those of full-scale flight operations. It also will provide some input data for the further evaluation of fuselage sound-proofing techniques.

Mounting a turboprop engine in the conventional manner in a wing nacelle will create interference drag between the wing and the nacelle, exaggerated by the

accelerated flow of the propeller slipstream. There is no previous experience that is applicable; earlier wing-nacelle interference studies were done with conventional airfoils rather than the supercritical one that undoubtedly would be used in any future turboprop transport. Wind-tunnel tests at the Ames Research Center have provided some basic force and pressure distribution data over a supercritical wing in the presence of a simulated slipstream from an advanced turboprop. Those studies point the way toward minimizing the interference drag increments. A more accurate estimate of the interference between the propulsion system and the airframe, including the effects on actual propeller performance, will be made using a powered propeller model.

There also is no previous experience available with which to design the structure of the new multi-bladed

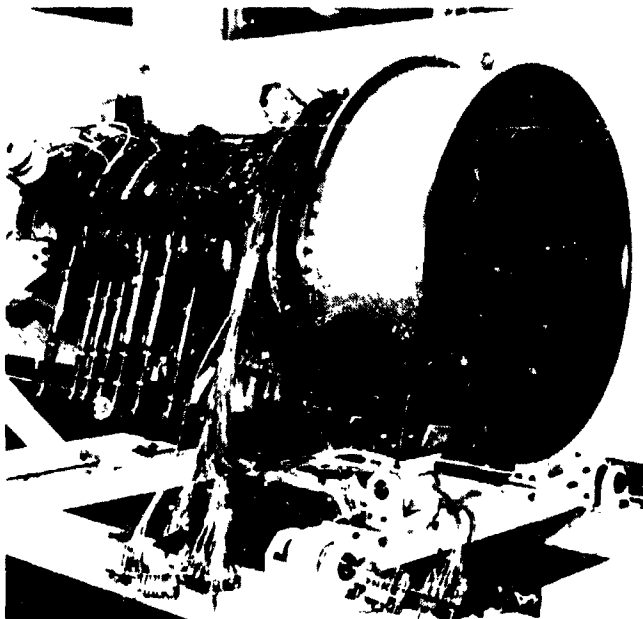


Figure 16: The test rig for the forward section of the high-pressure compressor is assembled prior to testing by General Electric. The compressor is one component of the Energy-Efficient Engine.

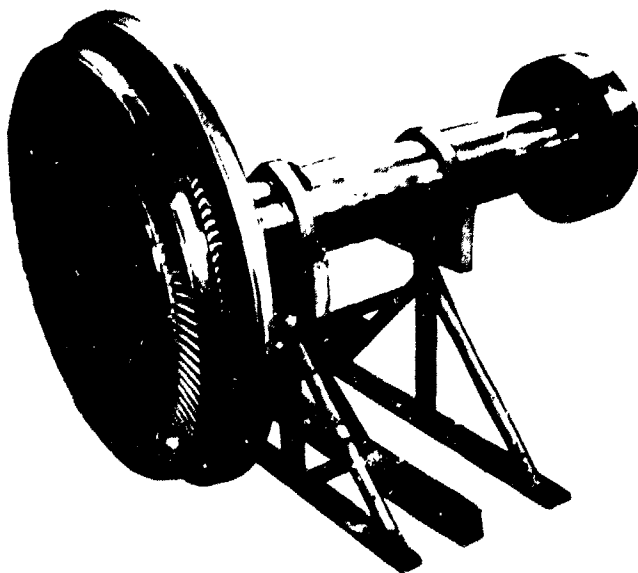


Figure 17: The first and second stage low-pressure turbine rotor assembly for General Electric's Energy-Efficient Engine.

propellers, so NASA is using its computerized structural analysis technique—a powerful design aid—to define the structural characteristics of these unusual propeller geometries.

Is there a turboprop aircraft in the future? All the early evaluation of the concept proved to be encouraging. First tests showed that the necessary propeller efficiencies could be attained, and that the aerodynamic performance of the propeller seemed to show no insuperable problems. The preliminary data on noise showed a



Figure 18: A scale model of a proposed mixer design is mounted for noise tests in General Electric's anechoic chamber. The mixer is a feature of GE's design for an Energy-Efficient Engine.

major reduction for the most recent advanced propeller model, compared to models tested earlier in the program.

Ultimately, then, the most fuel-efficient aircraft may be what at first appears to be a backward step. But its looks will be deceiving. The new transport will combine a supercritical wing with an advanced turboprop propulsion system, and will incorporate new structural design in the fuselage. The result could be a quiet, efficient airplane showing a major reduction in fuel consumption at little or no decrease in the performance to which we have become quite accustomed.

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